The Dependence of Moisture-tension Relationship and Water Availability on Irrigation Frequency in Containerized Growing Medium

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Abstract
An alternative definition of water availability is suggested and verified in the current study. According to this definition, the term water availability expresses the balance between the atmospheric water demand (Vapour pressure deficit, VPD) and the capability of the growing medium to supply this demand at the compatible rate. As such, water availability is a relative property that does not depend only on the levels of water content or tension in the growing medium. Water can be fully available at a certain VPD and partially available at a higher VPD, and vice versa. A controlled greenhouse study was conducted to verify the actual water availability under "wet" and "dry" irrigation treatments. The containers weight, water tension (tensiometers) and moisture content (TDR) at two heights within the container, and drainage from the container bottom were measured at 5 minutes interval. Water in the medium, at a certain tension, can be fully available at a particular VPD and partially available at a higher VPD, and vice versa. Water in the medium can be considered available, although not fully, if the pattern of water uptake rate follows the VPD daily pattern, namely, it does not decrease when VPD increases. A temporary high level of water availability is obtained during and soon after irrigation during high VPD hours which caused to a temporary increase in water uptake rate. Both, water availability and rate of water uptake decreased afterwards to the "smooth" pattern of uptake rate that is typical to the frequent irrigation treatment. This smooth pattern is higher than the water uptake rate pattern associated with the drier irrigation treatment. The relationship between the simultaneously-measured moisture content and water tension in the container (denoted as containerized-media retention curve) are different than the one measured in the laboratory when equilibrium in moisture content has been reached for each measured tension. The containerized-media retention curve is not unique; it depends on irrigation frequency and the location of the tensiometers and TDR probes within the container.

INTRODUCTION
An appropriate irrigation scheduling should increase the availability of water in the growing medium to the plant. The water flux through the medium–plant–atmosphere continuum can be determined by the van der Horst model. According to this model, the water flux is directly related to the potential difference, $h - \psi_L$, and inversely related to the overall hydraulic resistance along the continuum. The variable $h$ represents the water tension in the medium and $\psi_L$ is the leaf water tension. As such, the major aim of water application to the medium is to increase the medium potential, $\psi_s$. Nevertheless, the resistance to flow in the medium (unsaturated hydraulic conductivity, $K(h)$) is dependent in a non-linear manner on water tension (or water content). Minor variation of these two variables has a significant effect on $K(h)$ value (Wallach et al., 1992a,b; da Silva et al., 1993; Raviv et al., 2002). Therefore, the main purpose of irrigating media is to reduce temporarily the resistance to flow to the plant roots, namely, to increase water availability to the plant.

Frequent suction readings at different locations throughout the container by electro-
tensiometers provide continuous on-line information on suction distribution throughout the container. Tension data can be translated into moisture content by using a laboratory-measured retention curve of the medium (Wallach et al., 1992a). Means for the direct measurement of water content have recently been introduced (Kritz and Khaled, 1995; de Groot, 1995; da Silva et al., 1998). However, these equipments are still expensive and the translation of the measured parameters by these methods to moisture content requires an a priori calibration.

Ever since Bunt (1961) reported water retention curves for container media, much effort has been devoted to determining the usefulness of these curves in relating water availability to plant growth, and in quantifying such data both for descriptive and predictive purposes. The term EAW, suggested by De Boodt and Verdonck (1972) is based on the hidden assumption that the difference in water suction in the range of 1 – 5 kPa is of no physiological significance, as it is far lower than typical tensions applied by plant roots (normally in the range of 0.1 – 0.4 MPa). Thus, this term does not discriminate between water availabilities along the retention curve in the above range. However, the inherent restriction on water flux in many soilless media is not water tension. In fact, water flux is limited by unsaturated hydraulic conductivities \([K(h)]\) within a large part of this range. As \(K(\psi)\) greatly declines in most porous media with suction, the static approach of EAW has to be replaced by a more meaningful expression of water availability (Wallach et al., 1992a,b; da Silva et al., 1993; Raviv et al., 2002).

An alternative definition of water availability is suggested and verified in the current study. According to this definition, the term water availability expresses the balance between the atmospheric water demand (VPD) and the capability of the growing medium to supply this demand at the compatible rate. As such, water availability is a relative property that does not depend only on the levels of water content or tension in the growing medium. Water can be fully available at a certain VPD and partially available at a higher VPD, and vice versa.

**MATERIALS AND METHODS**

Rose plants (cv. Golden Gate, grafted on *Rosa indica* Major, cv. Sharon) were planted in 120 10-l buckets filled with tuff 0-8 mm (volcanic ash, scoria, Merom Golan, Israel) on August 17, 1999. The buckets were of 20 cm diameter and 21 cm height. The plants were drip irrigated with four l/hr drippers per bucket. Eight buckets were used for each replicate, five replicates for each irrigation frequency, all in a randomized block design. The nutrients were supplied with irrigation water (fertigation); it included 11, 1, and 4 mmolc of N, P, and K, respectively. The microelements were added as chelates.

Six buckets were selected, two for each irrigation frequency. These buckets were placed on load cells (Tadea-Huntleigh, Israel) that were connected to a data logger (CR10, Campbell, USA) via a multiplexer (AM214, Campbell, USA). Two TDR probes, 15 cm long, were installed vertically in each bucket. The upper one expands from the medium surface to 5 cm above the container bottom and the lower one is shifted 5 cm downward (almost reached the bottom). The TDR equipment consisted of Tektronix 1502B time-domain reflectometer (Tektronix, Inc., Beaverton, Oregon, USA), Electronic rain meters (tipping bucket type, Pronamic, Denmark) placed below the load cells collected the effluent from selected buckets.

Two high-flow electro-tensiometers (Ami Co, Israel) were installed horizontally in each bucket at 7 and 14 cm from the bottom, aside from the vertically installed TDR probes. The water tension read by each tensiometer could be considered as the tension at the middle of the vertically-installed TDR probes. All reading instruments were connected to the data logger and the 5-min-averaged readings were stored.

Three irrigation treatments were applied. The irrigation scheduling was automatically controlled according to predefined weight thresholds, so that there were three different irrigation frequencies: dry, intermediate and wet. The valves were closed when the bucket weight reached a high pre-defined threshold value. The reference threshold weight that turned the valve off was determined relative to the bucket weight at container capacity, namely, upon termination of the free drainage from the bucket bottom following an irrigation event. The upper threshold weight that eventually turned the valve off was 25% higher than the bucket weight at container capacity in order to enable leaching of excessive salts from the bucket.
RESULTS AND DISCUSSION

Container Weight, Tension and Moisture Content Variation

The variation of containers weight, tension at 14 and 7 cm above the container bottom, and the average water content along the upper (5-20 cm above the container bottom) and lower (0-15 cm above the container bottom) parts of the container are shown in Figure 1 for the wet (T1) and dry (T3) irrigation treatments during six (August 11-17, 2000) typical summer days. As expected from the method used to control the irrigation scheduling, the smaller amplitude of container-weight variation in the T1 treatment formed higher number of daily irrigation events. The irrigation events for this treatment took place mainly between the late morning and late afternoon hours when the atmospheric water demand was high (Fig. 1a, b). The tension and water content variations in the upper and lower parts of the T1- and T3-treatment containers followed the irrigation events (Fig. 1c, d and Fig. 1e, f, respectively). Overall, the tension in the upper and lower parts of the T1-treatment container was lower and the water content was higher than in the T3-treatment container. The difference between moisture contents measured by the upper and lower TDR probes was higher for the T1 than for T3 treatment.

For further and detailed analysis we arbitrarily choose two successive days from the six days: Aug 15 and 16, 2000. The container weight variation during these two days is shown in Figure 2 for T1 and T3 irrigation treatments. Close examination of the pattern of container weight variation during and between irrigation events (Fig. 2) indicates that it may be divided into three stages, dominated by different driving forces for moisture distribution within the container. During the first stage, while irrigation is on, the container weight markedly increases to a peak value (Fig. 2). During the 2nd stage, the container weight either stays constant if watering continues or decreases drastically when the irrigation is turned off, due to free water drainage. The duration of this stage and its intensity depend mainly on the hydraulic properties of the medium and on the container volume and geometry. Given that the time interval between any two data points in Fig. 2 is 5 min, the duration of this stage for the 10-l container volume was between 15 and 20 min for the T3 treatment and less for the T1 treatment. During the 3rd the weight continued to decrease at a much lower rate, through evaporation and water extraction by the roots. This stage extends up to the subsequent irrigation event. The moment when the 3rd stage started was determined by tracking the water discharge from the container bottom that was continuously measured by means of the tipping buckets. Since the container surface was fully covered by the plant canopy during the measurements, the contribution of evaporation to the weight loss was much smaller than that of transpiration (Urban et al., 1994) and can be practically ignored. Thus, in the calculations described below, the rate of container weight decrease during the 3rd stage is considered to be almost solely related to the transpiration-driven water uptake rate.

Water Uptake Rate (WUR) and Water Availability

Water uptake rate (WUR) by the plant can be calculated from the rate of container-weight decrease with time, namely, $\Delta W/\Delta t$. As the frequency of the container weight measurement increases, $\Delta W/\Delta t$ approaches the momentary WUR. Following the isolation of the 3rd stage, during which the container weight loss is attributed solely to the plant water uptake, the measured data was smoothed and the time derivative of the smoothed $W(t)$ was calculated. The WUR uptake patterns during the two days, together with the water application times (noted by the arrows), are shown in Figure 3 for the T1 and T3 treatments. The VPD during these two days, calculated from the measured air temperature and relative humidity by the Tetens method, are also shown in Figure 3.

As expected from the higher water content and lower tension distributions in the T1 container (Fig. 1), the momentary WUR for the T1 treatment was higher than for T3 treatment, during warmer hours (10:00-18:00) due to the high VPD values at this period. The lower VPD during the morning hours could be fully satisfied by the water flow to the roots under the given water content and tension in both T1- and T3-containers and having higher water content within the container had no advantage.

The WUR for the T1 treatment has a wavy pattern that is substantially different from the smooth pattern of the T3 WUR (Fig. 3). The WUR oscillations were linked with the
irrigation events; they increased soon after water application, reached a maximum, and decreased soon afterward. These WUR oscillatory were obtained only for irrigations events that took place during the mid-day hours when the VPD was high. The temporary WUR increase during and soon after water application were due to the sudden increase of water availability in the container as water content increased and tension decreased. This sudden increase of water availability enabled to fully meet the high VPD that could not be met at the relatively lower water availability prior to the water application event.

The response of the two irrigation treatments to the VPD increase on the second day (Aug 16, 2000) enable us to examine the suggested definition for water availability as a relative rather than an absolute attribute. The similar patterns of WUR in the T3 treatment during the two days, in spite of the higher VPD during the second day (Fig. 3), indicate that water was available to the plant during the two days, but not fully available to cope with the higher VPD in the second day. The statement that water was available relies on the pattern of WUR that followed the daily VPD variation pattern. If water availability was rather low, a decrease in WUR would be expected as VPD continues to increase. As opposed to T3 treatment, the WUR for T1 treatment was higher with higher oscillations amplitudes on Aug 16 than on Aug 15. This indicates that water availability in the T1 containers was higher due to the frequent irrigations and enabled to cope with the higher VPD on the second day.

Containerized-media Retention Curves

The variations of water content with tension measured simultaneously by the respective TDR probes and tensiometers at the upper and lower parts of the container are plotted in Figure 4 for the two irrigation treatments on Aug 15 and 16, 2000. The retention curve (RC) of the tuff that was independently measured in the laboratory is also added to Figure 4 as a reference. The water content vs. water tension as measured by a TDR and tensiometer couple in the container during and between subsequent irrigation events will be denoted in the following as "containerized-medium retention curve" – CRC. The laboratory measured retention curve for a sample of the growing medium will be denoted by RC. From Figure 4 one can conclude that: 1) CRCs are not identical to the RC, as might be expected – water content in the container according to the CRCs is in general lower than expected from the RC at lower tensions and higher than expected from the RC at higher tensions; 2) the CRC depends on the location within the container - different CRCs were obtained for the upper and lower parts of a container; 3) the CRC at the lower part of the container has a higher slope than the CRC at the upper part of the container, this indicates that the amount of water released per unit change in water tension is higher at the lower part of the container; 4) CRCs depends on the irrigation frequency - the CRC obtained for the less-frequent irrigation treatment (T3) was closer to the RC than the CRCs obtained for the T1 irrigation treatment; 5) The differences between CRCs for the upper and lower parts of the container is relatively higher at the frequent irrigations (T1); 6) The threshold tension from which the water content predicted by the CRC is higher than the RC depends on the irrigation frequency.

Water tension in the medium has been widely used to define the level of water availability to the plant. The findings in Figure 4 introduce a question mark on the relevance of evaluating the moisture content from measured tension by using the laboratory-measured RC. The deviations among the CRCs and RC are even more prominent when the tensiometers readings are used to evaluate the actual water availability to the plant under different irrigation frequencies and to calculate the unsaturated hydraulic conductivity by the eq. (2).

CONCLUSIONS

Being the balance between the atmospheric water demand (VPD) and the capability of the medium to supply this demand at a compatible rate, water availability is a relative rather than an absolute feature as was previously determined, mainly by relating it to water tension range. Water in the medium, at a certain tension, can be fully available at a particular VPD and partially available at a higher VPD, and vice versa. Water in the medium can be considered available, although not fully, if the pattern of water uptake rate follows the VPD daily pattern, namely, it does not decrease when VPD increases. When water uptake rate increases significantly during water application when VPD is high but varies smoothly along a normal daily patter, water in the growing media becomes highly available to meet fully the atmospheric demand. This high level of water availability is temporary and decreases soon
afterwards to the level of uptake rate that is typical to the frequent irrigation treatment, which is higher than the level associated with the drier irrigation treatment. The relationship between the simultaneously-measured moisture content and water tension in the container (denoted as containerized-media retention curve) are different than the one measured in the laboratory when equilibrium in moisture content has been reached for each measured tension. The containerized-media retention curve is not unique; it depends on irrigation frequency and the location of the tensiometers and TDR probes within the container.

Literature Cited
Fig. 1. Variation of container weight for (a) T1 and (b) T3 treatments, variation of upper and lower tension for the (c) T1 and (d) T3 treatments, and variation of water content in the upper and lower parts of the container for the (e) T1 and (f) T3 treatments during Aug 11-17, 2000.
Fig. 2. Variation of container weight for T1 treatment during Aug 15 (a) and Aug 16 (b), and T3 treatment during Aug 15 (c) and Aug 16 (d).
Fig. 3. Variation of water uptake rate during (a) Aug 15 and (b) Aug 16 for the T1 and T3 treatments together with the VPD variation during (c) Aug 15 and (d) Aug 16. Irrigations timing are indicated by arrows.

Fig. 4. Water content vs. water tension as was simultaneously measured by TDR probes and tensiometers, respectively, for the two irrigation treatments during Aug 15 and 16, 2000. The laboratory-measured retention curve for the tuff 0-8 is also shown for comparison.